IEEE TRANSACTIONS ON AEROSPACE / VOLUME 2 NUMBER 2 / APRIL 1964

4P.

N64 23913

code none

ANALYSIS OF A DISTRIBUTED SUPERCONDUCTIVE ENERGY CONVERTER

Andrew R. Sass
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

23913

SUMMARY

An equivalent circuit for a distributed superconductive energy converter, the operation of which is based on the principle of flux conservation in superconducting loops, is presented. The Laplace transformation is used to analyze the circuit, and the solutions are examined in order to optimize the operation of the device. While previously only dc operation of such a device has been realized, it is shown herein that under certain conditions a low frequency ac mode can be achieved.

AUTHOR

INTRODUCTION

The principle of flux conservation in a multiply connected superconductor has been utilized as the basis of a mechanoelectrical energy converter.[1] In the cited reference the flux of a magnet is trapped in a normal hole of a triply connected superconductor (Fig. 1). If the magnet is rotated mechanically, flux from the magnet continuously links the load inductor since the flux is conserved in each loop of the triply connected system. Current is thus built up in the load inductor. The limit of the device is the critical current of the load inductor since above this current the load becomes normally conducting.

Since the change of load current per cycle of magnet rotation α is small, the converter is essentially a dc generator. In order to realize an increase of α and to optimize the operation of the converter, an analysis of this type of device is needed.

The theoretical analysis of the converter shown in Fig. 1 is exceedingly difficult because of the complexity of the current distribution in the superconducting disk and the lack of symmetry of the device as a whole. The lack of symmetry may be overcome by considering a distributed superconductive energy converter (DSEC) shown in Fig. 2 (for simplicity only threefold symmetry is shown). The angle between two adjacent inductors (and two adjacent holes) is 120°.

The purpose of this paper is to present an "equivalent circuit" analysis for a DSEC with N-fold symmetry. The requirements for optimum operation of the DSEC will be derived. Very low frequency ac operation will be shown to be possible, and a typical design for such a mode will be discussed.[2]

ANALYSIS FOR THE DSEC

In Figs. 3(a) and (b), one section of an N-fold symmetric DSEC is shown. In the N-fold symmetric DSEC, the N load inductors are equally spaced (the angle between two adjacent inductors is 360°/N). Similarly the normally conducting holes remain equally spaced during the magnet rotation. The smallest spacing between the perimeters of two adjacent holes will be assumed to be smaller than the hole radius. In this case, the current will be confined to narrow paths, and an equivalent circuit analysis is justified.

An equivalent circuit for one section of the N-fold symmetric DSEC is shown in Fig. 3(c). The inductances associated with the current paths around the normally conducting holes are L_S and L_P. As a hole passes under L_0, L_1 varies from zero to L_S, and L_2 varies from L_S to zero. Assume that $n - 1$ holes have passed under L_0. The dynamics of the passage of the nth hole will now be described. The current in each element of the equivalent circuit (and the values of L_1 and L_2) before the hole passes under L_0 will be denoted by the additional subscript B. After the nth hole has passed under L_0, the subscript A will be used. When neither A nor B is used it will be understood that the quantity is expressed at an arbitrary time.

Because of the periodicity of the structure in question, it is evident from Fig. 3(c) that at every instant of time

$$i_1 = i_4 \tag{1}$$

and

$$v_2 = v_6 \tag{1'}$$

[1] J. Volger and P. S. Admiraal, "A Dynamo for Generating a Persistent Current in a Superconducting Circuit," Physics Letters, vol. 2, p. 257, 1962.

[2] During the writing of this paper, a similar symmetrical design was presented by S. L. Wipf, "A Superconducting D.C. Generator," Scientific Paper 63-128-280-PS Westinghouse Research Laboratories. Since only a rough analysis was used to explain the experimental results, the analysis in this paper can be utilized to make the Wipf design more efficient and adapt this type of generator for ac operation.

The first modification, shown in Fig. 4(a), makes use of a rectangular hole. This tends to increase L_S since L_S is a measure of the current flowing in a circumferential direction in the disk. By properly shaping the magnets, the rectangular geometry is easily realized. A magnetically permeable coating is also indicated. This coating tends to increase L_S and L_P more than it increases L_O. While the condition $\eta \gg 1$ will probably not be attained, a larger value than that of the design in Fig. 2 seems likely.

The second modification, shown in Fig. 4(b), consists of using inductive elements in place of the disk. All wires are high critical field superconductors except for the shaded portions, which simulate holes. The advantage of this scheme is that the values of L_S and L_P can be controlled. It is expected that this design will be superior to the first modification.

CONCLUSIONS

An analysis of the equivalent circuit of the DSEC indicates the possibility of efficient mechanoelectrical energy conversion. The equivalent circuit used, however, is only an approximation to the physical converter. The approximation is valid if the current is confined to narrow paths, approximating lumped element behavior. The analysis does not take into account hysteresis effects; however, this effect is judged to be small and in any case does not influence the buildup of flux in the load but only decreases the amount of recoverable energy. It was also assumed that the response of the hole to the motion of the magnet is instantaneous. Such an approximation is valid for rotational speeds that are less than 50 rpm.[3] Wipf[2] has shown that for a design similar to that shown in Fig. 2, a current of 40 amperes can be generated after 3600 turns. From equations (12) and (14) it appears that this amount of current could be generated in a fraction of a turn if the second modified design proposed herein is used. Thus, if the magnet array oscillates about an equilibrium position as was mentioned earlier, it is expected that ac currents of the order of 40 amperes and a frequency of 1 cps can be realized.

APPENDIX - EVALUATION OF i(k')

In order to find $i(k')$ when $n - 1 < k' < n$ (when the hole is in an intermediate position under L_O) it is merely necessary to note that

$$L_{1A} = kL_S \qquad L_{2A} = (1 - k)L_S \tag{A1}$$

where now the subscript A refers to the instant that the hole is in an intermediate position between L_{O1} and L_{O2}. Equations (4) and (5) become, respectively

$$L_O(i_{OA} - i_{OB}) - (1 - k)L_S i_{4A} + L_S i_{4B} - L_P(i_{2A} - i_{2B}) = 0 \tag{A2}$$

$$L_P(i_{2A} - i_{2B}) - L_O(i_{OA} - i_{OB}) - kL_S i_{3A} = 0 \tag{A3}$$

Solving as before shows that

$$i_O(k') = -i_2(k') = \frac{i_O(n - 1) - k\eta i_4(n - 1)}{1 + \eta k(1 - k)} \tag{A4}$$

$$i_1(k') = i_4(k') = \frac{(1 + k\eta)i_4(n - 1) - ki_O(n - 1)}{1 + \eta k(1 - k)} \tag{A5}$$

$$i_3(k') = \frac{i_4(n - 1) + (1 - k)i_O(n - 1)}{1 + \eta k(1 - k)} \tag{A6}$$

where $k' = n - 1 + k$ and $0 < k \leq 1$; $i_O(n - 1)$ and $i_4(n - 1)$ are given by equations (6) to (11).

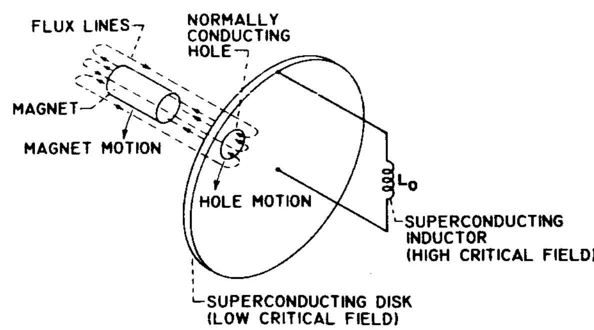

Figure 1. - Volger-Admiraal generator.

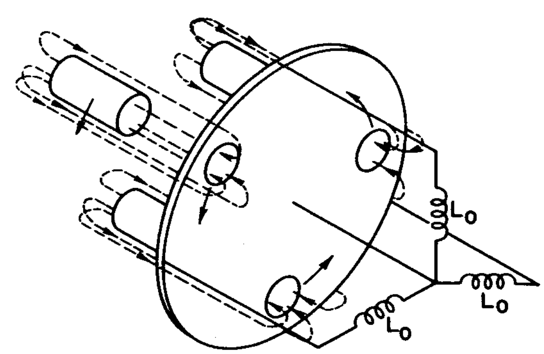

Figure 2. - DSEC: threefold symmetric.

[3]J. Vogler and J. van Suchtelen, "Induction of Heavy Persistent Currents," Conference on High Magnetic Fields, Their Production and Their Applications, Clarendon Laboratory, University of Oxford, July 10-12, 1963.